RSSAC023: History of the Root Server System

A Report from the ICANN Root Server System Advisory Committee (RSSAC)
4 November 2016

Preface

This is a report to the Internet community from the ICANN Root Server System Advisory Committee (RSSAC). In this report, the RSSAC gives an overview of the organizational history of the root server system.

The RSSAC advises the Internet community and ICANN Board of Directors on matters relating to the operation, administration, security and integrity of the Internet's Root Server System. The RSSAC's responsibilities include:

- Communicating with the technical and ICANN communities on matters relating to the operation of the root servers and their multiple instances.
- Gathering and articulating requirements to offer to those engaged in technical revisions of the protocols and common best practices related to the operation of DNS servers.
- Engaging in ongoing threat assessment and risk analysis of the Root Server System.
- Recommending necessary audit activity to assess the current status of root servers and the root zone.

Contributors to this report are listed at end of this document.

Table of Contents

1. Introduction

The Domain Name System (DNS) is a globally distributed, loosely coherent, scalable, reliable and dynamic database that provides a lookup mechanism for translating objects into other objects (e.g., domain names to IP addresses). The root servers are the entry points to the system because in the absence of other information, resolution for the domain name system starts at a root server.

In recent years, there has been renewed interest in understanding the history and evolution of the root server system. In this report, the RSSAC, in collaboration with root server operators, takes on the task of informing the community about the current root server system and its history from its beginnings to the present day.

The report is organized as follows:

- Section 2 is a chronological history of the root server system from its origin to its current structure. This description is divided into historical periods and also includes key events.
- Section 3 lists the root servers and gives historical information about the root zone operators and root service operations.
- Section 4 draws some conclusions based on the histories provided in sections 2 and 3.
- Section 5 contains appendices with information about the current root servers and their operators, historical copies of *root hints files* and acknowledgments.

This report focuses on the social and organizational history of the root server system. Specific technical aspects are covered only when they have an impact on the social and organizational history. Readers will find some technical events missing from this report. Notably absent are the introduction of Internet Protocol version 6 (IPv6) addresses for root servers, the Domain Name System Security Extensions (DNSSEC) signing of the root zone, the introduction of internationalized top-level domain names (IDNs), and the introduction in 2013 of new generic top-level domains (gTLDs). These developments are discussed elsewhere and did not have a significant impact on how DNS root servers are managed or used. Similarly, this report does not cover the formation and development of the Root Server System Advisory Committee (RSSAC).

2. History of Root Servers

2.1. Root Servers in Early Days of the DNS (1983–1986)

Before the development of the DNS, hosts in the Advanced Research Projects Agency Network (ARPANET) and Defense Data Network (DDN) were assigned names in a flat or global name space of character strings (e.g., USC-ISIF). The name-to-address translation was done by looking up the information in a table of all hosts. The maintenance of this table was centralized at the Network Information Center (NIC) at

SRI International, and each host was expected to obtain a current copy of the table on a timely basis from SRI-NIC.

As the size of the network grew, so did the number of hosts. The size of this table, and especially the frequency of updates to the table, were near the limit of manageability. What was needed was a distributed database that performed the same function, but avoided the problems caused by a centralized database. To address this bottleneck, in 1983, Jon Postel and Paul Mockapetris published a series of RFCs that laid out the design of the DNS[1] and the plan for transitioning the ARPANET to the DNS.[2,3]

To test the DNS software and further develop the Domain Name System, Jon Postel and Paul Mockapetris set up the first root server in 1984 at Information Sciences Institute (ISI) at the University of Southern California (USC). The server was running on a PDP-10[4] mainframe computer with software developed by Mockapetris called JEEVES. Since ISI was providing service to the ARPANET at the time, in 1985, an additional root server was added at ISI to better serve the ARPANET. In 1985, as the JEEVES software matured, SRI International hosted an additional root server. SRI International at the time was the NIC for DDN, and was responsible for handling the registration of hosts and maintenance of the hosts.txt file.

Doug Kingston and Mike Muuss, at the Ballistic Research Laboratory (BRL) in the U.S. Army, played an important role in the ongoing development of the Berkeley Internet Name Domain (BIND) package.[5] To assist in the further development of the DNS and to provide a root server for MILNET in the event that MILNET[6] had to be disconnected from the ARPANET, BRL volunteered in 1985 to host a root server,[7] making it the first root server running BIND on a UNIX operating system.

Thus by 1985, there were four root name servers, listed in Table 1.

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[1] Excerpts from RFC 882, "The proposed domain name system has three major components: The DOMAIN NAME SPACE, which is a specification for a tree structured name space. Conceptually, each node and leaf of the domain name space names a set of information,", "NAME SERVERS are server programs that hold information about the domain tree's structure and set information.", "RESOLVERS are programs that extract information from name servers in response to user requests."

[2] See RFCs 881, 882 and 883.

[3] Although the DNS was officially defined in RFC 881, 882 and 883, significant preparatory work by many contributors influenced its design. Some of this work is documented in RFC 805 and RFC 819.

[4] Interview with Paul Mockapetris, 13 August 2015.

[5] The BIND package was originally written for the BSD UNIX operating system as a Berkeley graduate student project under a grant from DARPA. Mike Karels at the University of California, Berkeley maintained the code. Doug Kingston and Mike Muuss at BRL later contributed significantly to the development of BIND.

[6] The MILNET, which was split from the original ARPANET in 1983, is the operational, unclassified network component of the Department of Defense Network.

[7] See http://marc.info/?l=namedroppers&m=95837667426459&w=2.

Table 1: List of Root Servers in 1985[8,9]

Name	IP Address	Software	Organization
SRI-NIC	10.0.0.51 26.0.0.73	JEEVES	SRI International
ISIB[10]	10.3.0.52	JEEVES	Information Sciences Institute, USC
ISIC	10.0.0.52	JEEVES	Information Sciences Institute, USC
BRL-AOS	192.5.25.82 128.20.1.2	BIND	Ballistic Research Laboratory, U.S. Army

When the Domain Name System drafts were first circulated for discussion, there was widespread agreement in the ARPANET community[11] that it was a promising solution to address the bottleneck of maintaining and distributing the hosts.txt file. Thus, Postel laid out a timeline and plan in RFC 881 for the ARPANET to transition to the DNS. Although the plan was delayed due to the introduction of top-level domains (TLDs), and was subsequently revised in RFC 897 and RFC 921, the transition did happen. By March 1987, SRI-NIC was named SRI-NIC.ARPA, ISIC was named C.ISI.EDU, BRL-AOS was named BRL-AOS.ARPA, and ISIA (previously ISIB[10]) was named A.ISI.EDU.[12]

2.2. Expanding Root Service for MILNET and NSFNET (1986–1990)

In 1986, with the ARPANET transition to domain names well underway, attention turned to MILNET's[13] transition. In October 1986, at the Internet Engineering Task Force (IETF) 6 meeting, Doug Kingston from BRL convened a workshop called "Name Domains for MILNET."[14] The primary focus was to explore the transition of MILNET to use domain names. The group proposed a three-step transition for MILNET:

1. Deploy root servers across MILNET, and remove non-domain names from the host table.

[8] See http://www.donelan.com/dnstimeline.html.
[9] See http://marc.info/?l=namedroppers&m=95837667426588&w=2.
[10] As the DNS was at early stages of development, root name servers at ISI tended to change machines frequently. In November 1986, ISIB was retired, and replaced by another server named ISIA. In October 1987, ISIC (C.ISI.EDU) was retired as well.
[11] Interview with Paul Mockapetris, 13 August 2015.

[12] See https://www.ietf.org/rfc/rfc1033.txt.
[13] The MILNET was split from the original ARPANET in 1983, as the operational, unclassified network component of the DDN, while ARPANET remained an advanced network R&D test bed for DARPA.
[14] See IETF 6 Proceedings: http://www.ietf.org/proceedings/06.pdf.

2. Assist MILNET in installing standard resolvers and servers, and then serve only domain-style names.
3. Ensure the NIC no longer supports the host table.

During the workshop and also in mailing list discussions afterwards, Gunter Air Force Station was mentioned as a possible root server location because of its ability to serve MILNET.[15] Eventually, in November 1987 GUNTER-ADAM (U.S. Air Force Networking Group) was added as a root server.

In 1986, the National Science Foundation Network (NSFNET) went online. Built as a "network of networks" and developed in phases, NSFNET connected supercomputer centers in the U.S. and a variety of regional research and education networks, extending the Internet's reach throughout the United States.[16]

As NSFNet traffic and registrations grew, people became aware of some cases of poor DNS service due to the limited number and reach of root servers. To address this issue, in July 1987, at the IETF 7 meeting, the name domain planning working group held a one-hour session to discuss root servers.[17] Attendees included Doug Kingston (BRL), Walt Lzaear (MITRE), Mark Lottor (SRI International), Louis Mamakos (University of Maryland), Mary Stahl (SRI International), Steve Wolff (National Science Foundation), Marty Schoffstall (Rensselaer Polytechnic Institute) and Hans-Werner Braun (University of Michigan). The goal of the meeting was to select root servers that would provide improved service to the NSFNET. The participants discussed and chose three new name servers:

- University of Maryland, largely because it was in a position to service equally well the NSFNET, ARPANET, MILNET and SURANET.[18]
- NASA Ames, because it was an ideal location due to its connection to MILNET, ARPANET, NASA-SCINET[19], NSFNET and BARRNET[20].
- Rensselaer Polytechnic Institute (RPI), which was part of the New York State Education and Research Network. It was also one of the first Internet service providers in the United States.[21]

These three root servers and GUNTER-ADAM were expected to be operational by IETF 8 in November 1987.

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[15] See http://marc.info/?l=namedroppers&m=95837759026807&w=2.
[16] See http://www.nsf.gov/od/lpa/news/03/fsnsf_internet.htm.
[17] See IETF 7 Proceedings: http://www.ietf.org/proceedings/07.pdf.
[18] SURANET (Southeastern Universities Research Assocation Network) was part of the first phase of National Science Foundation Network. Up and running in 1987, it was one of the first and one of the largest Internet proivders in the United States.
[19] Recommend a note here that briefly introduces NASA-SCINET.
[20] BARRNET, the Bay Area Regional Research network.
[21] See http://www.rpi.edu/dept/NewsComm/Magazine/Sep00/Pioneers.html.

In November 1987, C.ISI.EDU was retired from root server duty. As agreed, four additional root servers were added. Their IP addresses, software and organizations are listed in Table 2.

Table 2: List of Root Servers in November 1987[22]

Name	IP Address	Software	Organization
SRI-NIC.ARPA	10.0.0.51 26.0.0.73	JEEVES	SRI International
A.ISI.EDU	26.2.0.103	JEEVES	Information Sciences Institute, USC
C.NYSER.NET	128.213.5.17	BIND	Rensselaer Polytechnic Institute
TERP.UMD.EDU	10.1.0.17 128.8.10.90	BIND	University of Maryland
GUNTER-ADAM.ARPA	26.1.0.13	JEEVES	U.S. Air Force Networking Group
NS.NASA.GOV	128.102.16.10	BIND	NASA Ames
BRL-AOS.ARPA	192.5.25.82 128.20.1.2	BIND	Ballistic Research Laboratory, U.S. Army

In November 1988, DDN implemented phase two of the MILNET Domain Name Implementation with DDN MGT Bulletin 42.[23] As a result, SRI-NIC.ARPA was renamed to NIC.DDN.MIL, BRL-AOS.ARPA was renamed to AOS.BRL.MIL, and GUNTER-ADAM.ARPA was renamed to GUNTER-ADAM.AF.MIL.[24,25]

In April 1990, as part of phasing out the ARPANET, DDN issued Management Bulletin 72 that announced the following changes:[26]

- The new address for host NIC.DDN.MIL would be 192.67.67.20.
- The old ARPANET address for the NIC, 10.0.0.51, would be discontinued on 1 June 1990, the old MILNET address for the NIC, 26.0.0.73, would be discontinued on 1 June 1990.

[22] See http://marc.info/?l=namedroppers&m=95837781927013&w=2.
[23] See http://marc.info/?l=namedroppers&m=95837806326964&w=2.
[24] See https://github.com/sergev/4.4BSD-Lite2/blob/master/etc/namedb/root.cache.
[25] See http://marc.info/?l=namedroppers&m=95837784627013&w=2.
[26] See DDN MGTM Bulletin 72, http://marc.info/?l=namedroppers&m=95837797326928&w=2.

- The NIC's root domain name would run on a new host, NS.NIC.DDN.MIL, at address 192.67.67.53. The old server, running on NIC.DDN.MIL, would be discontinued on 1 June 1990.

Thus, by November 1990, there were seven root servers, listed in Table 3 below.

Table 3: List of Root Servers in November 1990[27,28]

Original Name	New Name	IP Address	Organization
SRI-NIC.ARPA	NS.NIC.DDN.MIL	192.67.67.53	SRI International
A.ISI.EDU	A.ISI.EDU	26.2.0.103 128.9.0.107	Information Sciences Institute, USC
C.NYSER.NET	C.NYSER.NET	192.33.4.12	RPI
TERP.UMD.EDU	TERP.UMD.EDU	128.8.10.90	University of Maryland
GUNTER-ADAM.ARPA	GUNTER-ADAM.AF.MIL	26.1.0.13	U.S. Air Force Networking Group
NS.NASA.GOV	NS.NASA.GOV	128.102.16.10 192.52.195.10	NASA Ames Research Center
BRL-AOS.ARPA	AOS.BRL.MIL	192.5.25.82 128.20.1.2	Ballistic Research Laboratory, U.S. Army

2.3. Expanding Root Service Outside North America (1991)

As the Internet developed in Europe in the late 1980s, there was an increasing need to have one or more root name servers in Europe to reduce the dependency on the few, expensive and unstable Internet links to the U.S. The issue was a topic of discussion at RIPE 1 on 22 May 1989.[29] The list of sites mentioned as possible root server hosts included:

- Royal Institute of Technology (KTH, the technical university) in Stockholm, Sweden
- Centrum Wiskunde & Informatica (CWI, the national research institute for mathematics and computer science) in Amsterdam, the Netherlands
- Conseil Européen pour la Recherche Nucléaire (CERN, the European physics research center) in Geneva, Switzerland/France

[27] See http://cd.textfiles.com/internetinfo/inet/ddn-news/ddn-mgt-bulletin-72.txt.
[28] Table 3 and forward will focus on root server organizations, and will not include software used by root servers.
[29] See https://www.ripe.net/participate/meetings/ripe-meetings/ripe-1.

At the time, the network operations center at the Royal Institute of Technology (later named the KTHNOC) operated three major networks in the area: the Swedish University Network (SUNET), the Swedish academic network, and the Nordic University Network (NORDUnet) connecting SUNET to its siblings in the other Nordic countries. Due to early adoption of the TCP/IP protocol suite in the Nordic region, NORDUnet was a very large "patch" on the Internet map in Europe, and serviced a large number of European users. The KTHNOC also managed domain names for Sweden (.se), and IP allocations for users in Sweden and within NORDUnet.

KTH/NORDUnet turned out to be a favorable location to host a root service because:

- NORDUnet was the first international wide-area multiprotocol network in the world, supporting TCP/IP, X.25, NJE of EARN, and DECnet protocols. The adoption of TCP/IP by NORDUnet allowed it to connect seamlessly to the Internet in the U.S.
- NORDUnet was one of the very few European networks to get a connection to the Internet in the U.S. In 1988, NORDUnet was connected via a 56 kbit/s satellite link to the John Von Neumann Center in Princeton, New Jersey.[30]
- NORDUnet had good connectivity to the rest of the Europe (EUnet, CERN).
- The staff operating NORDUnet had experience from operating DNS services for other high-profile domains, e.g., the national TLD for Sweden (.se).

On 28 July 1991, the server NIC.NORDU.NET was added to the root zone and became the first non-U.S. root server.

2.4. DDN-NIC Changes to Network Solutions (1991–1992)

In 1991, the Defense Information Systems Agency awarded the NIC contract to Government Systems, Inc. (GSI), which in turn outsourced the contract to Network Solutions, Inc. (NSI). As a result, a few changes happened:[31]

- The root server NS.NIC.DDN.MIL changed from 192.67.67.53 to 192.112.36.4.
- A.ISI.EDU was retired, and a new root server KAVA.NISC.SRI.COM would run at address 192.33.33.24, and take the place of A.ISI.EDU.

Table 4 lists the root servers that existed in October 1991.

[30] See http://www.nordu.net/history/TheHistoryOfNordunet_simple.pdf.
[31] See http://marc.info/?l=namedroppers&m=95837800227020&w=2.

Table 4: List of Root Servers in October 1991

Name	IP Address	Organization
NS.NIC.DDN.MIL	192.112.36.4	Network Solutions, Inc.
KAVA.NISC.SRI.COM	192.33.33.24	SRI International
C.NYSER.NET	192.33.4.12	NYSERnet
TERP.UMD.EDU	128.8.10.90	University of Maryland
NS.NASA.GOV	128.102.16.10 192.52.195.10	NASA Ames Research Center
NIC.NORDU.NET	192.36.148.17	NORDUnet
AOS.BRL.MIL	192.5.25.82	Ballistic Research Laboratory, U.S. Army

2.5. InterNIC (1993)

Since the 1980s, the registration of domain names was performed by the DDN-NIC under contract by the Department of Defense. This was because most registrants at the time were military users and awardees. By the early 1990s, due to the rapid growth of the NSFNET, academic institutions comprised the majority of new registrations, and the military was no longer willing to fund the registration for these names. The U.S. Federal Networking Council (a group of U.S. Government agencies involved in networking) asked the National Science Foundation (NSF) to assume responsibility for non-military Internet registration.[32]

In 1992, after a solicitation process (NSF 9224),[33] the NSF awarded three five-year cooperative agreements, to American Telephone and Telegraph Company (AT&T), General Atomics (GA), and Network Solutions, Inc. (NSI). The contracted parties were to provide directory and database services, information services and non-military registration services, respectively. These companies adopted the name InterNIC for their joint role.

Around the time Network Solutions won the bid to manage the domain registration service, it asked Jon Postel (IANA) about adding NS.INTERNET.NET as a root name server.[34] Postel agreed and IANA added NS.INTERNET.NET as a root server in April 1993 with IP address 198.41.0.4.

[32] See http://www.nsf.gov/od/lpa/news/03/fsnsf_internet.htm
[33] See http://www.nsf.gov/pubs/stis1992/nsf9224/nsf9224.txt.
[34] Interview with Mark Kosters.

In May 1994, KAVA.NISC.SRI.COM at SRI International was retired due to lack of funding, and NS1.ISI.EDU was added as a root server to replace it.[35]

In 1994, Paul Vixie and Rick Adams asked Jon Postel (IANA) on behalf of the Internet Software Consortium (ISC) to add a root server at ISC. Postel agreed, and in September 1994, IANA added NS.ISC.ORG as a root server. ISC was the organization coordinating the ongoing development and distribution of the most-used name server software, BIND, after taking over responsibility for BIND from Digital Equipment Corporation.

In October 1994, C.NYSER.NET changed to C.PSI.NET,[36] as part of the commercialization of the Internet service provider (ISP).[37]

2.6. Renaming Root Servers to root-servers.net (1995)

By April 1993, the number of root name servers had grown to an extent where the size of a *root hints* response was approaching the limit of 512 bytes. Bill Manning and Paul Vixie developed a plan to rename all root servers under the root-servers.net domain. This would allow the use of DNS label compression to fit all the names within 512 bytes. Postel (IANA) agreed with the plan and Mark Kosters began the renaming phases in 1995. Table 5 gives details about this renaming.

[35] See http://marc.info/?l=namedroppers&m=95837825027198&w=2
[36] See http://marc.info/?l=namedroppers&m=95837827527231&w=2.
[37] Although C.NYSER.NET changed to C.PSI.NET in 1994, the actual transition might have happened earlier. By one account, in late 1989, PSI acquired NYSERNet assets and established an ongoing outsourcing contract with NYSERNet. This acquisition gave PSINet commercial access to what would come to be known as the Internet. It is unclear whether the root server operated by NYSERNet was part of this transaction.

Table 5: Renaming of Root Servers in 1995

Original Name	New Name	Organization
NS.INTERNIC.NET	A.ROOT-SERVERS.NET	InterNIC (operated by NSI)
NS1.ISI.EDU	B.ROOT-SERVERS.NET	Information Sciences Institute, USC
C.PSI.NET	C.ROOT-SERVERS.NET	PSINet
TERP.UMD.EDU	D.ROOT-SERVERS.NET	University of Maryland
NS.NASA.GOV	E.ROOT-SERVERS.NET	NASA Ames Research Center
NS.ISC.ORG	F.ROOT-SERVERS.NET	Internet Software Consortium
NS.NIC.DDN.MIL	G.ROOT-SERVERS.NET	GSI (operated by NSI)
AOS.ARL.ARMY.MIL	H.ROOT-SERVERS.NET	U.S. Army Research Lab
NIC.NORDU.NET	I.ROOT-SERVERS.NET	NORDUnet

At the time of renaming, each letter identified a particular server machine. Today each letter identifies a single IPv4 address and a single IPv6 address, at which the service is provided under the responsibility of a single root server operator.

2.7. Adding Root Letters J, K, L and M

By moving to root-servers.net, operators were able to take advantage of DNS label compression,[38] leaving room for four additional root servers to fit within a 512 byte DNS response.[39] In January 1997, servers J-Root, K-Root, L-Root and M-Root, were added, serving the root zone exclusively. Postel (IANA) asked Network Solutions Inc. to set up two additional servers with the intention of moving them to suitable operators quickly

[38] Domain name compression was introduced in RFC1035 as an optional protocol feature and later mandated by RFC1123. In this scheme, an entire domain name or a list of labels at the end of a domain name is replaced with a pointer to a prior occurrence of the same name in the same message, thus eliminating the repetition of domain names in a message and reducing the size of the message. In the case of responses to root server priming queries, the domain root-servers.net appears only once in the response, instead of 13 times (once for each root server).

[39] The limitation is specified in RFC 1035 because at the time there were networks that could not handle DNS packets larger than 512 bytes without fragmenting. Also, known firewall rules dropped DNS packets more than 512 bytes in size.

thereafter. He kept two more servers at USC-ISI with the same intention. J-Root and K-Root were set up at Network Solutions on the U.S. East Coast, while L-Root and M-Root were at USC ISI on the U.S. West Coast.

From interviews, it appears that Jon Postel developed and used a few simple criteria in selecting organizations to host these new servers:[40]

- *Need:* The need for root server service. At the time, Europe had one operator. As the Internet developed in Europe, another root server would be useful. There were also no root servers in Asia, so a root server was needed there. The primary tool that Postel used to determine the need was Larry Landweber's International Connectivity Map.[41]
- *Connectivity*: The potential operator must have good connectivity both to the internal infrastructure[42] (internal connectivity), and to the world (external connectivity).
- *Community consensus:* The potential operator should demonstrate the widest possible support from the community being served.
- *Commitment to send and respond to traffic without filtering.* The operator must be able to answer every DNS query and send responses back unfiltered.

For the European region, a number of parties expressed their willingness to operate a second root name server. Jon Postel (IANA) encouraged all parties to seek consensus about the matter. After thorough discussion, there was consensus that the Réseaux IP Européens Network Coordination Centre (RIPE NCC) was the appropriate organization to operate the server because of its neutrality and technical expertise. In particular, the RIPE NCC was deemed able to change the server's deployment following changes in Internet topology.[43]

In the Asia Pacific Region, the Widely Integrated Distributed Environment (WIDE) organization was chosen.

These selections provided additional organizational diversity in the operation of root servers. Operators now included educational institutions, governments, commercial companies and not-for-profit service organizations.

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[40] Interview with Bill Manning, Suzanne Woolf, August 2015.
[41] See http://pages.cs.wisc.edu/~lhl/maps/.
[42] For example, connectivity within the country, within the region, or within a certain geography.
[43] At the time, all deployments were unicast. The RIPE DNS working group suggested deploying near or at one of the existing open exchange points. Consequently, the first deployment was at the LINX in London. The LINX contributed hosting and local hands, while the RIPE NCC provided the hardware and covered operations. This choice re-emphasized the independence of the location of the operator and the server itself. This was followed shortly thereafter by deployment of a hot standby at the AMS-IX.

In May 1997, K-Root (K.ROOT-SERVERS.NET) moved to London LINX, managed by RIPE NCC. In August 1997, M-Root (M.ROOT-SERVERS.NET) moved to Japan, managed by WIDE.

2.8. Root Server Meeting and Planning After Postel's Death

With K-Root and M-Root assigned, there remained two additional root servers to be assigned. Unfortunately, Jon Postel died on 16 October 1998, and there was no one to drive the process of assigning these additional root servers. J-Root stayed with NSI, and remained with Verisign after it acquired NSI in 2000.

Before Postel's death, it was planned that USC would transfer certain responsibilities, assets, and personnel to ICANN.[44] In 1999, this transfer occurred, which included L-Root.

The root server operators met for the first time as a formal group in December 1998 at IETF 43. They agreed to:

- Operate reliably, for the common good of the Internet.
- Recognize IANA as the source of the root data.
- Invest sufficiently to ensure responsible operation.
- Facilitate the transition, when needed and with proper notice.
- Recognize the other root server operators.

Several root server operators eventually produced similar statements that operationalized these principles (e.g., B-Root,[45] C-Root[46]).

The root sever operators also agreed to meet regularly as a group (root ops) to share information about root server operations, and to provide the Internet community with more information about the operation of the root servers. To this end, the group created a website listing all operators and giving news and other information about their operations.[47] The root ops group has been meeting regularly at IETF meetings to this day.

Section 5.1 of the appendix lists current root server names, their IP addresses and operators.

[44] Founded in 1998, Internet Corporation for Assigned Names and Numbers (ICANN) is a private not-for-profit public benefit corporation. It has performed the IANA functions on behalf of the global Internet community since the organization's creation in 1998.
[45] See https://b.root-servers.org/statements/operation.html.
[46] See http://c.root-servers.org/.
[47] See http://www.root-servers.org/.

3. Current Root Server Operators and Organization Histories

This section describes the 13 logical Internet root servers – current operators, histories and major commitments. The information was provided by current root zone operators.

3.1. A-Root

The A-Root Server (A.ROOT-SERVERS.NET) is operated by Verisign, Inc. Verisign cooperates with the 11 other root server operators to provide authoritative data for the DNS root zone.

Verisign, a global leader in domain names and Internet security, enables Internet navigation for many of the world's most recognized domain names and provides protection for websites and enterprises around the world. Verisign ensures the security, stability and resiliency of key Internet infrastructure and services, including the .com and .net domains and two of the Internet's root servers. Verisign also performs the root-zone maintainer functions for the core of the Internet's DNS. Verisign's Security Services include intelligence-driven Distributed Denial-of-Service Protection, iDefense Security Intelligence and Managed DNS.

Verisign views major obligations of being a root server operator to be:

- Operate A-Root and J-Root in a manner that exceeds all RFCs and advice from related committees.
- Serve the IANA root zone as distributed to Verisign from the root zone maintainer without modification.
- Always serve up-to-date data on its root servers.
- Meet ever-increasing demand by constantly improving performance, capacity and resiliency.
- Target capacity capabilities to accommodate 10×, 100×, 1000× regular peak denial-of-service attacks.
- Employ a worldwide deployment strategy to enable enough coverage and capacity to sustain worldwide demand.

Significant events and milestones for A-Root include:

Before the development of the DNS	Domain names and IP addresses were allocated by the NIC at SRI International. When the DNS was initially proposed in the early 1980s, SRI International operated one of three initial root name servers. Until late 1987, there were only four root name servers.
1991	The Defense Information Systems Agency awarded the NIC contract to GSI. GSI created a contract with NSI to run the NIC.
1993	NSI added NS.INTERNIC.NET as a root name server, with IP address 198.41.0.4. That same year its network connection was upgraded from 56K to T1 (1.5 Mbps).
Late 1993	The number of root name servers had grown to such an extent that the size of a *root hints* response was approaching the limit of 512 bytes. A plan was formed to rename all root servers under the ROOT-SERVERS.NET domain.
September 1995	NS.INTERNIC.NET was renamed to A.ROOT-SERVERS.NET.
2000	Verisign acquired Network Solutions, Inc.
2008	A-Root became a distributed service using IP anycast.
2008	The IPv6 address 2001:503:ba3e::2:30 was added for A-Root.

3.2. B-Root

The B-Root Server (B.ROOT-SERVERS.NET) is operated by the University of Southern California, a research university with a long history of Internet development and operations. B-Root is operated jointly by the USC Information Sciences Institute (ISI) and the USC Information Technology Services under the direction of the Computer Networks Division at USC ISI.

USC has operated B-Root since the inception of the root service system, when Jon Postel selected USC as an initial site. At the time, USC was leading the definition of DNS standards and was providing the IANA and RFC Editor functions; USC's operational participation accompanied those activities.

B-Root currently operates at a single site, providing root DNS service on IPv4 address 192.228.79.201 and IPv6 address 2001:500:84::b, with load sharing across multiple back-end computers. B-Root operates with commodity load balancing and runs Linux and BIND for its OS and server software. Through USC, B-Root peers with a number of regional and national networks.

USC is expecting to bring up a second site by the end of 2016. It expects to continue to operate with a relatively few sites, with an operational focus on supporting research and educational networks.

As a root server operator, B-Root is committed to serving the root zone reliably as one of the 12 organizations and participating in relevant coordination activities. In addition, as an academic organization, USC hopes that its operation of B-Root may foster collaboration between research and academia.

3.3. C-Root

The C-Root Server (C.ROOT-SERVERS.NET) is operated by Cogent Communications as a public service to the Internet. First operational in 1987, C.ROOT-SERVERS.NET was known as C.NYSER.NET and was established at the request of IANA.

In 1994, C.NYSER.NET became C.PSI.NET. PSINet, the first commercial ISP ever established, was operating the server when the root name server system started, using the root-servers.net domain, and thus became C.ROOT-SERVERS.NET.

In 2002, Cogent Communications acquired PSINet's major U.S assets, which included responsibility for operation of C.ROOT-SERVERS.NET. To promote the vital development of the global social and economic infrastructure, Cogent Communications has committed to the safe, reliable and secure operation of the root server for the benefit of the entire Internet. Instances of C.ROOT-SERVERS.NET are located in several locations throughout the United States and Europe.

3.4. D-Root

The D-Root Server (D.ROOT-SERVERS.NET) is operated by Advanced Cyber-Infrastructure Innovation Initiatives and Internet Global Services group at the University of Maryland, College Park, a public state university.

The University of Maryland was active in the early days of the DNS. During the IETF meeting held from 27 to 29 July 1987, the Name Domain Planning working group met. The working group recorded the following in its meeting report:

> "On the second day we held a one-hour meeting with a wider attendance to discuss root domain servers. In addition to the earlier attendees, we also had Steve Wolff (NSF), Marty Schoffstall (RPI) Hans-Werner Braun, and a few others. The impetus for this was the poor root nameserver service available on NSFNET and one goal of this meeting was to get some nameservers established that would provide good service to the NSFNET. We discussed and finally agreed on three new nameservers. Maryland and RPI were chosen fairly early on. Maryland was chosen in large part because it is in a position to service NSFNET, ARPANET, MILNET, and SURANET all equally well. After a bit more discussion we nominated NASA Ames and the third in absentia. Ames is an ideal location due to its connection to MILNET, ARPANET, NASA-Sci-Net, NSFNET?, and BARRNET?. Milo already had one of everything else, so he was happy to take on a root nameserver too. These three

servers and the server at Gunter Adam are expected to be fully operational by the next IETF meeting."

Currently D-Root anycasts the 199.7.91.13 address at 69 sites for a total number of 140 instances. The servers currently run BIND, but alternatives are under consideration.

Over the years, D-Root's operation has been headed by:

1987–1993	Louie Mamakos
1993–2011	Gerry Sneeringer
2011–2014	Jason Castonguay
2014–	Bruce Crabill

Additional support has been provided by Karl Reuss, Senior DNS Advisor, (1999–present) and Robel Regassa (2011–2014).

D-Root has been involved with RSSAC, with Gerry Sneeringer and Jason Castonguay attending the RSSAC meeting in 2011. From 2013–2014, our RSSAC representative was Tim Shortall. In 2014, Tripti Sinha took over the RSSAC representative role, and Gerry Sneeringer was appointed the alternate representative.

Significant events and milestones for D-Root include:

21 October 2002	There was a massive DDoS attack on the root name servers. Gerry Sneeringer of the University of Maryland co-authored an analysis report of that event with Paul Vixie (ISC) and Mark Schleifer (Cogent).[48]
June 2011	D-Root started supporting IPv6.
January 2013	In anticipation of moving to anycasting, D-Root was transitioned from its original UMD local IP address 128.8.10.90 (once known as TERP.UMD.EDU) to its current address, 199.7.91.13.
3 April 2013	UMD partnered with Packet Clearing House to provide expanded anycasting opportunities using server and network facilities in their various data centers around the world.

3.5. E-Root

The E-Root Server (E.ROOT-SERVERS.NET) is operated by National Aeronautics and Space Administration Ames Research Center (ARC). ARC, located in the heart of California's Silicon Valley, is one of 10 NASA field centers. For more than 75 years, ARC has led NASA in conducting world-class research and development in aeronautics,

[48] See the Report at http://d.root-servers.org/october21.txt.

exploration technology and science, aligned with the center's core capabilities. E-Root is managed and operated by staff from:

- NASA (U.S. Federal Government Agency)
- Ames Research Center (Silicon Valley)
- Code I (Ames Chief Information Office)
- Code IO (IT Operations Division)

In the late 1980s, NASA ARC was involved in creating networks (e.g., NASA Science Internet, Space Physics Analysis Network) in national and international universities and research institutions. The root server expansion to eight root servers was driven by the fact the growth of NSFNET required more resources. In 1987, NASA received ns.nasa.gov primarily because it had direct connections to the universities, research institutions and other networks, including MILNET, ARPANET, NASA-SCINET, NSFNET and BARRNET. The Federal Internet eXchange West (FIX-WEST) was implemented during this time as well.

Milo Medin, Jon Postel and Elise Gerich discussed Ames's role in deploying the root name server as NASA Ames Research Center was developing and operating the NASA Science Internet and the first Internet Exchange. NASA Science Internet was a leader in the IETF, and Milo was a major force behind the design and implementation of border gateway protocols.

Currently, E-Root operates at 1 core site with 91 anycast instances around the world. The servers are running BIND on FreeBSD. NASA ARC views its major obligation as a root server operator to be operating critical Internet infrastructure for the world, specifically, adhering to the recently clearly defined guidance provided in the RSSAC documents (e.g., RSSAC001 and RSSAC002) and engaging in the Internet community.

Significant events and milestones for E-Root include:

1988	The NASA Science Internet program was established as a multivendor, integrated approach to building an Internet working infrastructure and services for the NASA Space Sciences community worldwide. The NASA Science Internet program office was established at NASA ARC. This was a critical step forward in the evolution of networking, as NASA Science Internet led the creation of the Internet with the development and operational support of the first Federal Internet Exchange (FIX, originally called FEBA).
1991	The National Research and Education Network (NREN) led the charge in the development of high-speed networking in response to the needs of the U.S. Federal Government supercomputing community. NASA ARC was the program office for NASA NREN.
1997	NASA ARC led the Federal Government Joint Engineering Team in developing

	the Next Generation Internet technologies, speeds and applications in support of national goals and missions.
2011	NASA established a non-reimbursable space act agreement with Packet Clearing House to enable anycasting of E-Root.
2012	NASA acquired an AS and IPv6 addresses for E-Root from ARIN.
2013–2014	The three people who were the leads for supporting E-Root left the agency.
2014–2015	Three new leads for supporting E-Root were identified.

3.6. F-Root

The F-Root Server (F.ROOT-SERVERS.NET) is operated by Internet Systems Consortium, Inc. (ISC).[49] ISC is a 501(c)3 public benefit corporation. Founded in 1994 under an initial grant from UUNET, ISC is governed today by a five-member Board of Directors. ISC software, of which BIND and ISC DHCP are the two best-known examples, is open source. ISC is supported by donations from sponsors, by program membership fees and by increasing revenues from DNSco, a for-profit subsidiary.[50]

ISC has operated F-Root for IANA since 1994. F-Root currently answers queries over IPv4 on 192.5.5.241, and over IPv6 on 2001:500:2f::f using a hierarchical anycast technique and BIND 9 software.

Significant events and milestones for F-Root include:

2002	F-Root became the first root server to be anycasted internationally (Madrid was first outside of Palo Alto).[51] F-Root was also the first to use local area Open Shortest Path First Equal Cost Multipath (OSPF ECMP) for load balancing across multiple physical servers.
4 January 2008	ISC became the first root server operator to sign a Mutual Responsibilities Agreement[52] with ICANN.
2008	ISC F-Root's IPv6 address was changed, about three months after it first started using an IPv6 address, due to the need for a shorter BGP prefix.

[49] In 1994 when ISC first began to run a root name server, the company name was Internet Software Consortium. it was later changed to Internet Systems Consortium.
[50] For further information, see https://www.isc.org/supportisc.
[51] See https://www.nanog.org/meetings/nanog27/presentations/suzanne.pdf.
[52] See http://archive.icann.org/en/froot/ICANN-ISC-MRA-26dec07.pdf.

3.7. G-Root

The G-Root Server (G.ROOT-SERVERS.NET) is operated by the U.S. Department of Defense (DoD) Network Information Center (NIC). Based in Columbus, Ohio, DISA IE72 assumed control of the DoD NIC mission in 2005. This mission includes managing the G-Root, serving as the Internet registry for DoD and providing .mil registry/registrar services.

The DoD NIC employs 23 civilian government employees and 1 government contractor, and provides 24/7 support. Its major focus as a root server operator is to provide consistently reliable access and 100 percent availability to the G-Root anycast system, which serves the IANA authorized root zone.

Significant events and milestones for G-Root include:

Mid-1980s	G-Root can be traced back to an SRI-NIC server at address 26.0.0.73.
1990	Service at 26.0.0.73 ends, and is replaced by a server at 192.67.67.53 (called ns.nic.ddn.mil).
1991	Root server ns.nic.ddn.mil changed its address to 192.112.36.4 in conjunction with transferring the DDN NIC management contract from SRI International to GSI.
1995	Changed name to G.ROOT-SERVERS.NET.
1995	DDN NIC changed name to DoD NIC.
Mid-1990s	Contract to manage the DoD NIC (which includes the G-Root) is transferred from GSI to SAIC.
2005	DoD NIC operations and management transferred from SAIC to a DISA civilian-staffed government office in Columbus, Ohio.
2006	The .mil zone is removed from the root servers that had been providing authoritative support (A, B, E, F, G, and H).
2008	Anycast implemented for G-Root at six locations.
20 October 2016	The IPv6 address 2001:500:12::d0d was added for G-Root.

3.8. H-Root

The H-Root Server (H.ROOT-SERVERS.NET) is operated by the U.S. Army Research Laboratory (ARL), formerly known as the Ballistics Research Laboratory (BRL), which has a long history of being a leader in the computing and networking arenas. BRL was the home of the world's first electronic digital computer, ENIAC, and one of the first 50 sites to have a web server on the Internet. Many BRL/ARL researchers were involved in the early development of UNIX, the Internet and TCP/IP protocols (including the DNS).

BRL was one of the first and one of the most well connected nodes on the ARPANET/MILNET in the late 1970s and early 1980s. As such, BRL volunteered to host one of the original root servers – both to assist in the further development of the DNS and to provide a root server for the MILNET in the event that MILNET had to be disconnected from the Internet. Currently, ARL is home to one of the world's largest supercomputing facilities and resides on the high-speed Defense Research and Engineering Network (DREN), which ARL scientists helped design. To this day, ARL continues to operate a root name server as a service to the Internet community.

Notes of interest:

- BRL sponsored the development and was the home of ENIAC. Until May 23, 2013, the H-Root server was located in the same building as ENIAC.
- Mike Muuss,[53] author of the ping utility, and Doug Kingston, both BRL employees, were involved in early BIND development.[54] They were instrumental in establishing a root server at BRL/ARL and were two of the original operators.
- Today, ARL operates one of the five U.S. Department of Defense supercomputing centers (http://www.arl.hpc.mil).

Currently, H-Root is operated in two sites, primary in Aberdeen Proving Ground, Maryland, and a hot spare in San Diego, California. Each site is load balanced across multiple nodes. All nodes run NSD and support both IPv4 and IPv6.

Significant events and milestones for H-Root include:

1985	BRL-AOS (aos.brl.mil) added as one of the first four root servers and the first one to be running BIND (released on April 1, 1985). It was a VAX-11/780 (5 MHz) and its IP addresses were 192.5.25.82 and 128.20.1.2.
Before November 1991	26.3.0.29 address added to AOS.
Before November 1991	128.63.4.82 address added to AOS.
Between November 1992 and May 1994	128.20.1.2 address removed from AOS.
Between March 1993 and May 1994	26.3.0.29 address removed from AOS.
1992	U.S. Army's Ballistic Research Laboratory (BRL) incorporated into the newly established Army Research Laboratory (ARL), BRL is dissolved.
3 April 1994	aos.brl.mil renamed to aos.arl.army.mil.

[53] See https://en.wikipedia.org/wiki/Mike_Muuss.
[54] See http://web.archive.org/web/20081118071434/https://www.isc.org/software/bind/history.

1995	AOS (VAX-11/780) replaced with a Sun SPARC 5 (70/85/110 MHz).
18 August 1995	aos.arl.army.mil renamed to H.ROOT-SERVERS.NET. IP address changed from 128.63.4.82/192.5.25.82 to 128.63.2.53.
August 1998	H transitions from Sun SPARC 5 to 168-MHz Sun Ultra-2.
~2000	.com, .net, and .org zones removed from H.
10 June 2001	H transitions from 168-MHz Sun SPARC 5 running Solaris to a 1.2 GHz Intel system running Linux.
9 December 2002	IPv6 support added to H at address 2001:500:1::803f:235 (no AAAA's added to root zone until 2008).
9 December 2002	H load balanced across multiple nodes (IPv4 only).
10 November 2003	One instance of H converted from BIND to NSD.
2004	All instances of H converted to NSD.
31 October 2006	.mil zone removed from H.
4 February 2008	IPv6 AAAA record for H (along with five other root servers) added to the root zone.
14 March 2010	H begins serving DNSSEC signed .arpa zone.
14 April 2010	H begins serving unvalidatable DNSSEC signed root zone.
15 July 2010	All root servers begin serving valid DNSSEC signed root zone.
16 December 2010	Hot spare instance brought online at SPAWAR in San Diego.
28 February 2011	H stops serving in-addr.arpa zone.
17 March 2011	IPv6 added to load balancing.
1 December 2015	IP addresses changed to 198.97.190.53 and 2001:500:1::53 in the root and root-servers.net zones.

3.9. I-Root

The I-Root Server (I.ROOT-SERVERS.NET) is currently operated by NetNod.

In a coordinated effort in 1995, all root servers were renamed into one domain. NIC.NORDU.NET was renamed to I.ROOT-SERVERS.NET.

As the Internet developed in Europe Internet exchange points (IXs) were introduced. One of the first European IXs was established by the networking staff at the KTH in Stockholm.

Networking in the 1990s was infected by hindering traffic policies. NORDUnet, despite having an extremely open traffic policy, ran the risk of being accused of prohibiting traffic to the root name server, and decided to move it, from inside NORDUnet, to its own service provider connected directly to the IX in Stockholm. That way, an independent and totally open peering policy could be set for I-Root.

The exchange point was eventually spun off from the KTH to a separate corporate structure created for the purpose, with a foundation (TU-stiftelsen) owning a limited not-for-profit company (Netnod[55]) that operates the service. In 2000, Netnod created a subsidiary called Autonomica for the purpose of tying specialist DNS staff closer to the company, and NORDUnet and Autonomica operated in close cooperation to provide the service.

The Internet continued to shift from academic to commercial, and with NORDUnet focused on its work on the academic side, it made sense to shift responsibilities. In 2004, NORDUnet and Autonomica made an agreement that shifted all practical responsibilities to Autonomica – to facilitate administration and financial support for the service. According to the agreement, NORDUnet remained as a last resort, guaranteeing the service in the event of Netnod's demise and inability to provide it.

Eventually Autonomica and Netnod were merged into one company, retaining the Netnod organization and name. Netnod assumed all of Autonomica's responsibilities, which included the NORDUnet agreement and the operations of I-Root.

In an open letter to ICANN in 2009, Netnod affirmed the mutual commitment to coordination of DNS root name service operations, acknowledging that a single, unique DNS root is paramount to the stable operations of the Internet and to ensuring global reachability.[56]

On the technical side, I-Root started back in 1991 as a single Sun 3/50 machine with 4 MB of RAM. It evolved through the 1990s with single server Sun SPARC systems, until, in 1998, PC clones were employed for a few years, shifting over to Digital Equipment Alpha servers, with one operating machine and one hot spare. Eventually Netnod shifted back to PCs in 2002. To further improve robustness and availability of the service, Netnod started to make use of the anycast model in 2003, where servers are deployed at different sites across the entire Internet, but still use a single IP address. As of November 2015, Netnod operates a worldwide system of more than 50 sites – with local routers, support servers and traffic analyzers at each site.

Netnod manages a robust constellation of servers around the globe, and intends to further expand the I.ROOT-SERVERS.NET server footprint in the coming years.

[55] Formally, Netnod Internet Exchange i Sverige AB, http://www.netnod.se/.
[56] See http://www.netnod.se/joint-rootserver-statement-icann.

Netnod commits to serving complete and unmodified DNS data (including DNSSEC signatures) from the global root zone, exactly as received from the root zone maintainer, to the global Internet community.

3.10. J-Root

The J-Root Server (J.ROOT-SERVERS.NET) is operated by Verisign, Inc. Verisign cooperates with the 11 other root server operators to provide authoritative data for the DNS root zone.

J-Root receives DNS queries over IPv4 at 192.58.128.30 and over IPv6 at 2001:503:c27::2:30. J-Root uses IP anycast to provide service from a large number of locations throughout the world, which may change from time to time.

Significant events and milestones for J-Root include:

1997	J.ROOT-SERVERS.NET was added as the 10th root name server. Operated by Network Solutions, it was initially co-located with A-Root and used the IP address 198.41.0.10.
2000	Verisign acquired Network Solutions, Inc.
2002	J-Root was renumbered to 192.58.128.30, thus allowing it to be anycasted.
2008	IPv6 address 2001:503:c27::2:30 was added for J-Root.

3.11. K-Root

The K-Root Server (K.ROOT-SERVERS.NET) is operated by the Réseaux IP Européens Network Coordination Centre (RIPE NCC). The K-Root service is provided by a set of distributed nodes using IPv4 and IPv6 anycast. Each node announces prefixes from 193.0.14.0/23 in AS25152. Additionally, some nodes announce prefixes from 2001:7fd::/32 in AS25152. A K-Root node consists of one or more servers running BIND, Knot or NSD.

The RIPE NCC is a not-for-profit membership association under Dutch law. Its membership consists mainly of Internet service providers, telecommunications organizations and large corporations. Currently there are more than 12,000 members from more than 100 countries. RIPE NCC is governed by its general assembly and Executive Board, and is guided by the RIPE community.

The RIPE NCC has provided root service reliably since 1997, at its members' expense and for the benefit of the Internet as a whole. The RIPE NCC recognizes that a single, unique DNS root is vital to the stable operations of the Internet and to ensure global reachability. It fully shares the views expressed by the Internet Architecture Board in RFC 2826.

ICANN establishes global consensus about the content of the root zone, compiles and maintains it, and makes it available to the RIPE NCC and other DNS root name server operators, all in accordance with its governance processes. Through K.ROOT-SERVERS.NET, the RIPE NCC publishes the DNS root zone to Internet users in a non-discriminatory fashion, following the relevant technical standards and best practices, and in accordance with RIPE NCC governance processes.

ICANN and the RIPE NCC have affirmed their mutual commitment to coordinating DNS root name service operations through an open exchange of letters in 2009. These letters acknowledged that a single, unique DNS root is paramount to the stable operations of the Internet and to ensuring that it can be accessed across the globe.[57]

RIPE NCC remains committed to these principles, and will continue working to put them into operation, independent of changes to the IANA stewardship.

The quality of service of K-Root, and other root name servers, is continuously monitored from thousands of RIPE Atlas probes deployed around the Internet. The RIPE DNSMON service provides analyses of this monitoring for name server operators. All these measurements and analyses are available to the general public.

The RIPE NCC continuously evaluates and evolves the technical implementation of K-Root to provide high quality service to all Internet users, with some emphasis on the RIPE region. The service is continuously augmented to meet peak loads and provide continuous service while under attack.

Resources:

- General information about the RIPE NCC and its governance: http://www.ripe.net
- General information about K-Root: http://k.root-servers.org/
- RIPE NCC's current expansion plan is available at: http://k.root-servers.org/hosting.html
- Monitoring: https://dnsmon.ripe.net/ https://atlas.ripe.net/

[57] See https://ripe.net/s/kr2h.

Significant events and milestones for K-Root include:

19 May 1997	K-Root went live from servers located at the LINX operated by the RIPE NCC. A hot standby set of servers was deployed at the AMS-IX shortly afterwards.
Early 2000s	Most root server operators have always had a preference for open source name server software because of the auditability it provides. This is important for the root, both for debugging and for general transparency. In early 2000s, there were increasing concerns about the lack of diversity in open source name server software. The RIPE NCC partnered with NLnet Labs to design and develop an authoritative name server (NSD)[58] from scratch. The RIPE NCC contributed requirements, input to the design and lab testing to the initial development of NSD.
2003	NSD was deployed on K-Root.
2003	K-Root deployed anycast based on the hot standby in Amsterdam.[59]
4 February 2008	K-Root service became available on IPv6.

3.12. L-Root

The L-Root Server (L.ROOT-SERVERS.NET) is currently operated by the Internet Corporation For Assigned Names and Numbers (ICANN). ICANN is a not-for-profit public-benefit corporation with participants from all over the world dedicated to keeping the Internet secure, stable and interoperable. It promotes competition and develops policy on the Internet's unique identifiers. Through its coordination role of the Internet's naming system, it has an important impact on the expansion and evolution of the Internet.

In 2000, ICANN became operator of L-Root with John Crain as ICANN CTO and commenced plans to anycast L-Root.

ICANN sees that the major obligation of being the L-Root server operator is to transparently provide global service of root zone resolution from L-Root in the face of all operational and political concerns.

The expansion of L-Root continues, along with the incremental improvements in engineering practices.

The L-Root system currently operates at IPv4 address 199.7.83.42 with the range 199.7.83.0/24, and at IPv6 address 2001:500:3::42 with the range 2001:500:3::/48. Both ranges are announced from AS20144. L-Root is currently anycasted at over 145 locations

[58] See http://www.nlnetlabs.nl/projects/nsd/.
[59] See https://www.ripe.net/publications/docs/ripe-268.

on both IPv4 and IPv6. L-Root runs both Name Server Daemon (NSD) from NLnet Labs and Knot software platforms on both Linux and BSD.

Significant events and milestones for L-Root include:

November 2007	L-Root changed its IPv4 address from 198.32.64.12 to 199.7.83.42 in zone serial 2007110201.
December 2008	L-Root added its IPv6 address (2001:500:3::42) to the root zone in zone serial 2008121201.
2013	Terry Manderson took over management of the DNS Operations Department.
2014	The DNS Operations Department was moved into the ICANN IT function and renamed DNS Engineering.

3.13. M-Root

The M-Root Server (M.ROOT-SERVERS.NET) is jointly operated by the WIDE Project and Japan Registry Services (JPRS). The WIDE Project is a research project based in Japan, focusing on networking and distributed technologies. JPRS is the ccTLD registry operator of .jp, and plays a role in gTLD registry and registrar operations.

The discussion of the distribution of the root servers was made on the Internet Engineering and Planning Group (IEPG) meetings around 1995 and 1996. Japan was proposed as one of the additional locations, with the WIDE Project as its operator. The note from the June 1996 IEPG meeting stated:

> "The IEPG proposed to draft an IEPG Operational Note, proposing to IANA an experimental deployment of 2 additional name servers, with proposed locations in the UK (Linx) and Japan (WIDE Project) and proposed timing, duration and objectives of the experiment to be documented (Action: Bill Manning)."[60]

At the December 1996 IEGP meeting, after further discussion, Jun Murai (Founder of the WIDE Project) received an appointment to operate a root server in Tokyo, Japan.

In December 2005, JPRS joined the operation of M-Root by a request from the WIDE Project – to provide more operational and financial stability.[61]

Currently, the IP addresses for M-Root are: (IPv4) 202.12.27.33 and (IPv6) 2001:dc3::35. M-Root is anycasted at the following locations: Tokyo, Japan (three sites); Osaka, Japan;

[60] See http://www.iepg.org/june1996/index.html.
[61] See http://www.wide.ad.jp/news/press/20051220-RootDNS-e.html and http://jprs.co.jp/press/2005/051220.html (Japanese).

Paris, France; San Francisco, California, U.S.; and Seoul, Korea. Each location provides both IPv4 and IPv6 transport.

As the root server operator, WIDE and JPRS consider their joint obligation is to support the operational stability of the root servers for all Internet users.

Significant events and milestones for M-Root include:

1997	WIDE Project started M-Root operation in Tokyo, Japan.
2001	Redundant operation using "Anycast in Rack" started.
2001	Backup site in Osaka, Japan, launched.
2004	Anycast deployment started in Seoul, Korea, and Paris, France,[62] and San Francisco, USA.
2005	JPRS joined the operation.
2008	IPv6 address added in the root zone and root-servers.net zone.
2009	ICANN and the WIDE Project exchanged letters about M-Root operation.[63]

4. Conclusions

The root server system began at Information Science Institute in 1984. At the time it was used to develop the Domain Name System and to test the DNS software. As the software matured, network information centers (e.g., SRI International, Network Solutions) started to host root servers. The root server system developed to meet the needs of the growing interconnected networks – from ARPANET, MILNET, NSFNET – to the global Internet.

Today, the DNS root (name) servers make the DNS root zone available to all DNS users on the Internet. The servers are operated by 12 independent organizations. As operators, they publish the authoritative root zone without modification.

Dr. Jon Postel chose the organizations based on technical expertise, Internet connectivity and diversity, considering both their organizations and operating practices. Today, entities that operate root servers include government network information centers, laboratories, universities, for-profit organizations and not-for-profit service associations. There is great diversity in the operational history and approaches of root servers, as well as hardware and software. This diversity in aspects such as geography, organizations and operations has enabled the root server system to deal with local challenges, avoid capture by any single party and provide reliable service to the Internet community.

[62] See http://www.wide.ad.jp/news/press/20040929-dns-e.html.
[63] See https://www.icann.org/en/system/files/files/murai-to-twomey-06may09-en.pdf.

The system has always provided reliable service to the Internet community. The root server system has evolved over more than three decades in all aspects: number and diversity of the operators, capacity and connectivity of servers, diversity of DNS software, IPv6 capability, and last but not least, anycast.

5. Appendixes

5.1. Current Root Server name, IP Address and Operator

Hostname	IP Addresses	Operator
A.ROOT-SERVERS.NET	198.41.0.4, 2001:503:ba3e::2:30	Verisign, Inc.
B.ROOT-SERVERS.NET	192.228.79.201, 2001:500:84::b	Information Sciences Institute, USC
C.ROOT-SERVERS.NET	192.33.4.12, 2001:500:2::c	Cogent Communications
D.ROOT-SERVERS.NET	199.7.91.13, 2001:500:2d::d	University of Maryland
E.ROOT-SERVERS.NET	192.203.230.10	NASA Ames Research Center
F.ROOT-SERVERS.NET	192.5.5.241, 2001:500:2f::f	Internet Systems Consortium, Inc.
G.ROOT-SERVERS.NET	192.112.36.4 2001:500:12::d0d	U.S. Department of Defense Network Information Center
H.ROOT-SERVERS.NET	198.97.190.53, 2001:500:1::53	U.S. Army Research Lab
I.ROOT-SERVERS.NET	192.36.148.17, 2001:7fe::53	Netnod
J.ROOT-SERVERS.NET	192.58.128.30, 2001:503:c27::2:30	VeriSign, Inc.
K.ROOT-SERVERS.NET	193.0.14.129, 2001:7fd::1	RIPE NCC
L.ROOT-SERVERS.NET	199.7.83.42, 2001:500:3::42	ICANN
M.ROOT-SERVERS.NET	202.12.27.33, 2001:dc3::35	WIDE Project and JPRS

5.2. Historical Copies of Root Hint File or Root Cache File

Operators who manage a DNS recursive resolver typically need to configure a *root hints file*. This file contains the names and IP addresses of the root zone, so the software can bootstrap the DNS resolution process. For many pieces of software, this list comes built into the software.

5.2.1. March 1993

Source: http://alpha.tmit.bme.hu/pub/netinfo/hosts/root07.zon[64]

```
.     IN    SOA   NS.NIC.DDN.MIL.   HOSTMASTER.INTERNIC.NET. (
                        930311      ;serial
                        10800  ;refresh every 3 hours
                        900    ;retry every 15 minutes
                        604800 ;expire after a week
                        86400  ;minimum of a day
                        )
                          518400     NS    NS.NIC.DDN.MIL.
NS.NIC.DDN.MIL.           518400     A     192.112.36.4
.                         518400     NS    AOS.BRL.MIL.
AOS.BRL.MIL.              518400     A     128.63.4.82
                          518400     A     26.3.0.29
                          518400     A     192.5.25.82
.                         518400     NS    KAVA.NISC.SRI.COM.
KAVA.NISC.SRI.COM.        518400     A     192.33.33.24
.                         518400     NS    C.NYSER.NET.
C.NYSER.NET.              518400     A     192.33.4.12
.                         518400     NS    TERP.UMD.EDU.
TERP.UMD.EDU.             518400     A     128.8.10.90
.                         518400     NS    NS.NASA.GOV.
NS.NASA.GOV.              518400     A     128.102.16.10
                          518400     A     192.52.195.10
.                         518400     NS    NIC.NORDU.NET.
NIC.NORDU.NET.            518400     A     192.36.148.17
```

5.2.2. December 1993

The oldest BIND source code available is for version 4.9.2, dating back to around December 1993. This package contains the following “conf/root.cache” file:

```
;; QUESTIONS:
;;   ., type = NS, class = IN
;; ANSWERS:
.    518400    NS   NS.INTERNIC.NET.
.    518400    NS   AOS.ARL.ARMY.MIL.
.    518400    NS   KAVA.NISC.SRI.COM.
.    518400    NS   C.NYSER.NET.
.    518400    NS   TERP.UMD.EDU.
.    518400    NS   NS.NASA.GOV.
.    518400    NS   NIC.NORDU.NET.
.    518400    NS   NS.NIC.DDN.MIL.

;; ADDITIONAL RECORDS:
NS.INTERNIC.NET. 518400   A    198.41.0.4
AOS.ARL.ARMY.MIL.    518400    A    128.63.4.82
AOS.ARL.ARMY.MIL.    518400    A    192.5.25.82
KAVA.NISC.SRI.COM.   518400    A    192.33.33.24
C.NYSER.NET.   518400    A    192.33.4.12
TERP.UMD.EDU.  518400    A    128.8.10.90
NS.NASA.GOV.   86400 A   128.102.16.10
NS.NASA.GOV.   86400 A   192.52.195.10
NIC.NORDU.NET.   518400   A    192.36.148.17
```

[64] TLD information is omitted.

```
NS.NIC.DDN.MIL.  518400   A    192.112.36.4
;; FROM: gw.home.vix.com to SERVER: ns.nasa.gov  128.102.16.10
;; WHEN: Sun Dec 19 13:42:51 1993
;; MSG SIZE  sent: 17  rcvd: 402
```

5.2.3. Nov 1995

Source: http://uw714doc.sco.com/en/man/html.4tcp/root.cache.4tcp.html

```
;       This file holds the information on root name servers needed to
;       initialize cache of Internet domain name servers
;       (e.g. reference this file in the "cache  .  <file>"
;       configuration file of BIND domain name servers).
;
;       This file is made available by InterNIC registration services
;       under anonymous FTP as
;           file                /domain/named.root
;           on server           FTP.RS.INTERNIC.NET
;       -OR- under Gopher at    RS.INTERNIC.NET
;           under menu          InterNIC Registration Services (NSI)
;              submenu          InterNIC Registration Archives
;           file                named.root
;
;       last update:    Nov 8, 1995
;       related version of root zone:   1995110800
;
;
; formerly NS.INTERNIC.NET
;
.                        3600000  IN  NS    A.ROOT-SERVERS.NET.
A.ROOT-SERVERS.NET.      3600000      A     198.41.0.4
;
; formerly NS1.ISI.EDU
;
.                        3600000      NS    B.ROOT-SERVERS.NET.
B.ROOT-SERVERS.NET.      3600000      A     128.9.0.107
;
; formerly C.PSI.NET
;
.                        3600000      NS    C.ROOT-SERVERS.NET.
C.ROOT-SERVERS.NET.      3600000      A     192.33.4.12
;
; formerly TERP.UMD.EDU
;
.                        3600000      NS    D.ROOT-SERVERS.NET.
D.ROOT-SERVERS.NET.      3600000      A     128.8.10.90
;
; formerly NS.NASA.GOV
;
.                        3600000      NS    E.ROOT-SERVERS.NET.
E.ROOT-SERVERS.NET.      3600000      A     192.203.230.10
;
; formerly NS.ISC.ORG
;
.                        3600000      NS    F.ROOT-SERVERS.NET.
F.ROOT-SERVERS.NET.      3600000      A     192.5.5.241
;
; formerly NS.NIC.DDN.MIL
;
.                        3600000      NS    G.ROOT-SERVERS.NET.
```

```
G.ROOT-SERVERS.NET.      3600000      A     192.112.36.4
;
; formerly AOS.ARL.ARMY.MIL
;
.                        3600000      NS    H.ROOT-SERVERS.NET.
H.ROOT-SERVERS.NET.      3600000      A     128.63.2.53
;
; formerly NIC.NORDU.NET
;
.                        3600000      NS    I.ROOT-SERVERS.NET.
I.ROOT-SERVERS.NET.      3600000      A     192.36.148.17
; End of File
```

5.2.4. Feb 1997

```
Source: http://marc.info/?l=namedroppers&m=95837845327369&w=2

;       This file holds the information on root name servers needed to
;       initialize cache of Internet domain name servers
;       (e.g. reference this file in the "cache  .  <file>"
;       configuration file of BIND domain name servers).
;
;       This file is made available by InterNIC
;       under anonymous FTP as
;           file                /domain/named.root
;           on server           FTP.RS.INTERNIC.NET
;       -OR- under Gopher at    RS.INTERNIC.NET
;           under menu          InterNIC Registration Services (NSI)
;              submenu          InterNIC Registration Archives
;           file                named.root
;
;       last update:    Feb 28, 1997
;       related version of root zone:   1997022800
;
; formerly NS.INTERNIC.NET
;
.                        3600000      NS    A.ROOT-SERVERS.NET.
A.ROOT-SERVERS.NET.      3600000      A     198.41.0.4
;
; FORMERLY NS1.ISI.EDU
;
.                        3600000      NS    B.ROOT-SERVERS.NET.
B.ROOT-SERVERS.NET.      3600000      A     128.9.0.107
;
; FORMERLY C.PSI.NET
;
.                        3600000      NS    C.ROOT-SERVERS.NET.
C.ROOT-SERVERS.NET.      3600000      A     192.33.4.12
;
; FORMERLY TERP.UMD.EDU
;
.                        3600000      NS    D.ROOT-SERVERS.NET.
D.ROOT-SERVERS.NET.      3600000      A     128.8.10.90
;
; FORMERLY NS.NASA.GOV
;
.                        3600000      NS    E.ROOT-SERVERS.NET.
E.ROOT-SERVERS.NET.      3600000      A     192.203.230.10
;
; FORMERLY NS.ISC.ORG
```

```
;
.                       3600000      NS    F.ROOT-SERVERS.NET.
F.ROOT-SERVERS.NET.     3600000      A     192.5.5.241
;
; FORMERLY NS.NIC.DDN.MIL
;
.                       3600000      NS    G.ROOT-SERVERS.NET.
G.ROOT-SERVERS.NET.     3600000      A     192.112.36.4
;
; FORMERLY AOS.ARL.ARMY.MIL
;
.                       3600000      NS    H.ROOT-SERVERS.NET.
H.ROOT-SERVERS.NET.     3600000      A     128.63.2.53
;
; FORMERLY NIC.NORDU.NET
;
.                       3600000      NS    I.ROOT-SERVERS.NET.
I.ROOT-SERVERS.NET.     3600000      A     192.36.148.17
;
; temporarily housed at NSI (InterNIC)
;
.                       3600000      NS    J.ROOT-SERVERS.NET.
J.ROOT-SERVERS.NET.     3600000      A     192.41.0.10
;
; temporarily housed at NSI (InterNic)
;
.                       3600000      NS    K.ROOT-SERVERS.NET.
K.ROOT-SERVERS.NET.     3600000      A     198.41.0.11
;
; temporarily housed at ISI (IANA)
;
.                       3600000      NS    L.ROOT-SERVERS.NET.
L.ROOT-SERVERS.NET.     3600000      A     198.32.64.12
;
; temporarily housed at ISI (IANA)
;
.                       3600000      NS    M.ROOT-SERVERS.NET.
M.ROOT-SERVERS.NET.     3600000      A     198.32.65.12
; End of file
```

5.2.5. May 2015

```
;       This file holds the information on root name servers needed to
;       initialize cache of Internet domain name servers
;       (e.g. reference this file in the "cache  .  <file>"
;       configuration file of BIND domain name servers).
;
;       This file is made available by InterNIC
;       under anonymous FTP as
;           file                /domain/named.cache
;           on server           FTP.INTERNIC.NET
;       -OR-                    RS.INTERNIC.NET
;
;       last update:    May 23, 2015
;       related version of root zone:   2015052300
;
; formerly NS.INTERNIC.NET
;
.                       3600000      NS    A.ROOT-SERVERS.NET.
A.ROOT-SERVERS.NET.     3600000      A     198.41.0.4
```

```
A.ROOT-SERVERS.NET.      3600000      AAAA  2001:503:ba3e::2:30
;
; FORMERLY NS1.ISI.EDU
;
.                        3600000      NS    B.ROOT-SERVERS.NET.
B.ROOT-SERVERS.NET.      3600000      A     192.228.79.201
B.ROOT-SERVERS.NET.      3600000      AAAA  2001:500:84::b
;
; FORMERLY C.PSI.NET
;
.                        3600000      NS    C.ROOT-SERVERS.NET.
C.ROOT-SERVERS.NET.      3600000      A     192.33.4.12
C.ROOT-SERVERS.NET.      3600000      AAAA  2001:500:2::c
;
; FORMERLY TERP.UMD.EDU
;
.                        3600000      NS    D.ROOT-SERVERS.NET.
D.ROOT-SERVERS.NET.      3600000      A     199.7.91.13
D.ROOT-SERVERS.NET.      3600000      AAAA  2001:500:2d::d
;
; FORMERLY NS.NASA.GOV
;
.                        3600000      NS    E.ROOT-SERVERS.NET.
E.ROOT-SERVERS.NET.      3600000      A     192.203.230.10
;
; FORMERLY NS.ISC.ORG
;
.                        3600000      NS    F.ROOT-SERVERS.NET.
F.ROOT-SERVERS.NET.      3600000      A     192.5.5.241
F.ROOT-SERVERS.NET.      3600000      AAAA  2001:500:2f::f
;
; FORMERLY NS.NIC.DDN.MIL
;
.                        3600000      NS    G.ROOT-SERVERS.NET.
G.ROOT-SERVERS.NET.      3600000      A     192.112.36.4
;
; FORMERLY AOS.ARL.ARMY.MIL
;
.                        3600000      NS    H.ROOT-SERVERS.NET.
H.ROOT-SERVERS.NET.      3600000      A     128.63.2.53
H.ROOT-SERVERS.NET.      3600000      AAAA  2001:500:1::803f:235
;
; FORMERLY NIC.NORDU.NET
;
.                        3600000      NS    I.ROOT-SERVERS.NET.
I.ROOT-SERVERS.NET.      3600000      A     192.36.148.17
I.ROOT-SERVERS.NET.      3600000      AAAA  2001:7fe::53
;
; OPERATED BY VERISIGN, INC.
;
.                        3600000      NS    J.ROOT-SERVERS.NET.
J.ROOT-SERVERS.NET.      3600000      A     192.58.128.30
J.ROOT-SERVERS.NET.      3600000      AAAA  2001:503:c27::2:30
;
; OPERATED BY RIPE NCC
;
.                        3600000      NS    K.ROOT-SERVERS.NET.
K.ROOT-SERVERS.NET.      3600000      A     193.0.14.129
K.ROOT-SERVERS.NET.      3600000      AAAA  2001:7fd::1
```

```
;
; OPERATED BY ICANN
;
.                        3600000      NS    L.ROOT-SERVERS.NET.
L.ROOT-SERVERS.NET.      3600000      A     199.7.83.42
L.ROOT-SERVERS.NET.      3600000      AAAA  2001:500:3::42
;
; OPERATED BY WIDE
;
.                        3600000      NS    M.ROOT-SERVERS.NET.
M.ROOT-SERVERS.NET.      3600000      A     202.12.27.33
M.ROOT-SERVERS.NET.      3600000      AAAA  2001:dc3::35
; End of file
```

5.2.6. October 2016

```
;       This file holds the information on root name servers needed to
;       initialize cache of Internet domain name servers
;       (e.g. reference this file in the "cache  .  <file>"
;       configuration file of BIND domain name servers).
;
;       This file is made available by InterNIC
;       under anonymous FTP as
;           file                /domain/named.cache
;           on server           FTP.INTERNIC.NET
;       -OR-                    RS.INTERNIC.NET
;
;       last update:    October 20, 2016
;       related version of root zone:   2016102001
;
; formerly NS.INTERNIC.NET
;
.                        3600000      NS    A.ROOT-SERVERS.NET.
A.ROOT-SERVERS.NET.      3600000      A     198.41.0.4
A.ROOT-SERVERS.NET.      3600000      AAAA  2001:503:ba3e::2:30
;
; FORMERLY NS1.ISI.EDU
;
.                        3600000      NS    B.ROOT-SERVERS.NET.
B.ROOT-SERVERS.NET.      3600000      A     192.228.79.201
B.ROOT-SERVERS.NET.      3600000      AAAA  2001:500:84::b
;
; FORMERLY C.PSI.NET
;
.                        3600000      NS    C.ROOT-SERVERS.NET.
C.ROOT-SERVERS.NET.      3600000      A     192.33.4.12
C.ROOT-SERVERS.NET.      3600000      AAAA  2001:500:2::c
;
; FORMERLY TERP.UMD.EDU
;
.                        3600000      NS    D.ROOT-SERVERS.NET.
D.ROOT-SERVERS.NET.      3600000      A     199.7.91.13
D.ROOT-SERVERS.NET.      3600000      AAAA  2001:500:2d::d
;
; FORMERLY NS.NASA.GOV
;
.                        3600000      NS    E.ROOT-SERVERS.NET.
E.ROOT-SERVERS.NET.      3600000      A     192.203.230.10
E.ROOT-SERVERS.NET.      3600000      AAAA  2001:500:a8::e
;
```

```
; FORMERLY NS.ISC.ORG
;
.                        3600000      NS    F.ROOT-SERVERS.NET.
F.ROOT-SERVERS.NET.      3600000      A     192.5.5.241
F.ROOT-SERVERS.NET.      3600000      AAAA  2001:500:2f::f
;
; FORMERLY NS.NIC.DDN.MIL
;
.                        3600000      NS    G.ROOT-SERVERS.NET.
G.ROOT-SERVERS.NET.      3600000      A     192.112.36.4
G.ROOT-SERVERS.NET.      3600000      AAAA  2001:500:12::d0d
;
; FORMERLY AOS.ARL.ARMY.MIL
;
.                        3600000      NS    H.ROOT-SERVERS.NET.
H.ROOT-SERVERS.NET.      3600000      A     198.97.190.53
H.ROOT-SERVERS.NET.      3600000      AAAA  2001:500:1::53
;
; FORMERLY NIC.NORDU.NET
;
.                        3600000      NS    I.ROOT-SERVERS.NET.
I.ROOT-SERVERS.NET.      3600000      A     192.36.148.17
I.ROOT-SERVERS.NET.      3600000      AAAA  2001:7fe::53
;
; OPERATED BY VERISIGN, INC.
;
.                        3600000      NS    J.ROOT-SERVERS.NET.
J.ROOT-SERVERS.NET.      3600000      A     192.58.128.30
J.ROOT-SERVERS.NET.      3600000      AAAA  2001:503:c27::2:30
;
; OPERATED BY RIPE NCC
;
.                        3600000      NS    K.ROOT-SERVERS.NET.
K.ROOT-SERVERS.NET.      3600000      A     193.0.14.129
K.ROOT-SERVERS.NET.      3600000      AAAA  2001:7fd::1
;
; OPERATED BY ICANN
;
.                        3600000      NS    L.ROOT-SERVERS.NET.
L.ROOT-SERVERS.NET.      3600000      A     199.7.83.42
L.ROOT-SERVERS.NET.      3600000      AAAA  2001:500:9f::42
;
; OPERATED BY WIDE
;
.                        3600000      NS    M.ROOT-SERVERS.NET.
M.ROOT-SERVERS.NET.      3600000      A     202.12.27.33
M.ROOT-SERVERS.NET.      3600000      AAAA  2001:dc3::35
; End of file
```

6. Acknowledgments

The RSSAC would like to thank the following root server operators, members of the RSSAC Caucus and external experts for their time, contributions and review in producing this report.

Root Server Operators

A-Root	Verisign, Inc.
B-Root	University of Southern California
C-Root	Cogent Communications
D-Root	University of Maryland
E-Root	NASA Ames
F-Root	Internet System Consortium
G-Root	U.S. Department of Defense Network Information Center
H-Root	U.S. Army Research Lab
I-Root	NetNod
J-Root	Verisign, Inc.
K-Root	RIPE NCC
L-Root	ICANN
M-Root	WIDE Project and JPRS

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